Strategic Storage Use in a Hydro-Thermal Power System with Carbon Constraints

Sébastien Debia, HEC Montréal, sebastien.debia@hec.ca
Pierre-Olivier Pineau, HEC Montréal, pierre-olivier.pineau@hec.ca
Afzal S. Siddiqui, University College London, Stockholm University, and HEC Montréal, afzal.siddiqui@ucl.ac.uk

Overview

The Northeast Power Coordinating Council (NPCC) comprises American states and Canadian provinces marked by a significant penetration of variable renewable energy sources (VRES) and hydropower production. Major demand centres in New England, New York, Ontario, and Québec that are subject to stringent to stringent caps on CO_2 emissions are included in the NPCC. For example, the Regional Greenhouse Gas Initiative (RGGI) mandates a 30% reduction in CO_2 emissions from power plants by 2030 relative to 2020 levels, which affects generation in New England and New York. Likewise, Québec participates in the Western Climate Initiative (WCI), which aims to reduce CO_2 emissions by approximately 40% by 2030 relative to 1990 levels and included Ontario until recently. Both RGGI and WCI create cap-and-trade (C&T) systems for CO_2 emissions in which the shadow price on the binding CO_2 emission constraint is the permit price that generators incur as an additional cost for their CO_2 emissions. While support schemes such as feed-in tariffs and the C&T system have induced an increase in VRES generation, they have also enhanced the role of energy storage, viz., by hydro reservoirs especially in Québec. In a perfectly competitive power system, storage capacity would be deployed in a socially optimal way to smooth out the fluctuations in uncontrollable VRES output (Bushnell, 2003). However, given the persistence of market power in the electricity industry (Tangerås and Mauritzen, 2018), hydro reservoirs may be used in a strategic manner to the benefit of their proprietors. Consequently, incentives for VRES and social welfare may be detrimentally affected by such exertion of market power. In order to investigate the extent of these distortions in the NPCC and to propose policies for their mitigation, we develop a bottom-up equilibrium model to quantify the welfare losses from the strategic use of hydropower reservoirs and to assess counterfactual CO_2 emission caps.

Methods

Following Hobbs (2001), we develop a game-theoretic framework with firms, consumers, and an independent system operator (ISO). Each firm owns several plants and maximises its profit via its production decisions, while consumers are represented by nodal inverse-demand functions. The ISO determines welfare-maximising power flows with transmission constraints and Kirchhoff's laws represented via a direct-current approximation, and generation portfolios are based on installed capacities. We reflect seasonal variations in VRES output and demand along with the topology of hydropower reservoirs. Although hydro producers are allowed to spill water in all cases, a regulatory constraint requiring a majority of the water to be used for generation is implemented. A system-wide C&T constraint internalises the CO_2 emission restriction. We implement (i) a perfect competition model with price-taking firms (PC) and (ii) a Cournot oligopoly setting in which selected firms exercise market power while the rest behave as a competitive fringe (CO). Both PC and CO could be represented as either a mixed-complementarity problem, in which each agent's problem is replaced by its first-order Karush-Kuhn-Tucker conditions, or a quadratic program.

Results

In order to quantify the welfare losses from the strategic use of hydropower reservoirs, we run four test cases (Table 1) both with and without CO_2 emission caps. In cases PC-NR and CO-NR, hydropower plants are treated as being run-of-river stations, which enables us to investigate the impact of reservoir capacity, i.e., storage, on social welfare and CO_2 emissions. The problem instances are implemented in GAMS and solved to optimality via CPLEX.

Table 1. Test Cases

Market Status / **Storage Status**	*Perfect Competition*	*Cournot Oligopoly*
No Hydro Reservoirs	PC-NR	CO-NR
Hydro Reservoirs (status quo)	PC-SQ	CO-SQ

Prior to investigating the NPCC test cases, we first develop problem instances based on a simplified three-node network incorporating thermal, VRES, and hydro production. In Table 2, we present the results without a C&T system in place and quantify the impact of market power on welfare (where "SW," "CS," "PS," and "MS" stand for "social welfare," "consumer surplus," "producer surplus," and "merchandising surplus," respectively) and environmental indicators (where "EM" refers to "emissions"). First, under the status quo cases, i.e., with hydro reservoirs, market power has intuitively straightforward effects, i.e., a transfer of surplus from consumers to producers with reductions in both social welfare and CO_2 emissions due to less consumption. In particular, hydro producers leave more water in their reservoirs in the terminal period, thereby increasing their nodal prices above the perfectly competitive levels. Here, the "Δ" column calculates the difference in the corresponding metric from permitting market power. Second, the removal of reservoir capacity, i.e., treatment of hydro plants as run-of-river facilities, diminishes the impact of market power as the "Δ" column has generally smaller values in magnitude. Intuitively, the removal of storage from hydro producers disrupts their ability to manipulate prices. Consequently, they effectively produce the perfectly competitive level of output and resort to spilling water in order to mitigate the detrimental effect of losing storage flexibility. At the same time, while the loss in flexibility in going to case PC-NR from PC-SQ generally harms social welfare under PC (albeit with a surplus transfer to consumers from producers), a similar transition to CO-NR from CO-SQ improves CS to a greater extent.

Table 2. Market Power Impact (in k$) without C&T

Test Case / **Metric**	*PC-SQ*	*CO-SQ*	*Δ*	*PC-NR*	*CO-NR*	*Δ*
SW	29.412	27.894	-1.518	29.349	27.844	-1.505
CS	25.316	21.073	-4.243	26.868	23.124	-3.744
PS	3.487	6.122	2.635	1.837	3.972	2.135
MS	0.610	0.699	0.09	0.644	0.749	0.105
EM (t CO_2)	199.488	110.512	-88.976	194.512	110.512	-84

A similar set of test cases is next implemented but with a binding CO_2 emission cap of 100 t (Table 3), which means a drastic cut in emissions for the PC cases in line with NPCC policies. An active C&T system leads to a positive price for CO_2 permits in all test cases with a corresponding inclusion of government revenue (GR) in the welfare calculation. Furthermore, in the status quo cases, since the C&T system affects the PC-SQ results to a greater extent, the corresponding impact of market power (captured by the "Δ" column) is generally smaller in magnitude than that in Table 2 without a C&T system. Finally, without hydro reservoirs and with the regulatory restriction on spilling water, the loss in social welfare due to the exercise of market power is completely eliminated as the only difference between PC-NR and CO-NR stems from the difference in PS and GR due to the CO_2 permit price.

Table 3. Market Power Impact (in k$) with 100 t CO_2 Emission Cap

Test Case / **Metric**	*PC-SQ*	*CO-SQ*	*Δ*	*PC-NR*	*CO-NR*	*Δ*
SW	27.565	27.558	-0.007	27.508	27.508	0
CS	21.244	20.752	-0.492	22.802	22.802	0
PS	2.271	5.569	3.298	0.619	3.419	2.8
MS	0.724	0.712	-0.012	0.762	0.762	0
GR	3.326	0.526	-2.8	3.326	0.526	-2.8
CO_2 Permit Price ($/t)	33.256	5.256	-28	33.256	5.256	-28

Conclusions

Using a three-node test network with a modest VRES penetration, we have quantified the impact of market power by linking it to the additional flexibility available to hydro producers. Virasjoki et al. (2018) take a similar approach to investigating the role of combined heat and power in facilitating price manipulation in the Nordic region. In a system with greater VRES penetration, the possibly welfare-diminishing impact of hydro reservoirs under CO may be outweighed by their benefits in VRES integration. Towards that end, we will next use NPCC data to calibrate our model, i.e., the observed prices and generation mixes are bounded by those produced from our PC and CO implementations, before proceeding with a similar investigation.

References

Bushnell, J. (2003), "A Mixed Complementarity Model of Hydrothermal Electricity Competition in the Western United States," *Oper. Res.* 51, 80–93.

Hobbs, B.F. (2001), "Linear Complementarity Models of Nash–Cournot Competition in Bilateral and POOLCO Power Markets," *IEEE Trans. Power Syst.* 16(2): 194-202.

Tangerås, T. and J. Mauritzen (2018), "Real-Time versus Day-Ahead Market Power in a Hydro-Based Electricity Market," *J. Ind. Econ.*, forthcoming.

Virasjoki, V., A.S. Siddiqui, B. Zakeri, and A. Salo (2018), "Market Power with Combined Heat and Power Production in the Nordic Energy System," *IEEE Trans. Power Syst.* 33(5): 5263-5275.